Oceanography of the Indonesian Seas

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LONG-TERM GOALS

The Indonesian Seas provide a pathway for substantial transfer of Pacific waters to the Indian Ocean. The Indonesian Throughflow (ITF) strongly influences the heat and freshwater budgets of these two oceans and is considered a key component in the ENSO and monsoon climate phenomena. The meridional circulation, stratification, sea surface temperature and sea level of the Indian and Pacific Oceans would be very different if the ITF were zero. The long-term goal is to quantify these statements.

OBJECTIVES

The objectives of the Arlindo Project, a joint oceanographic research endeavor of Indonesia and the United States are: to define the magnitude and variations of the ITF mass, heat and freshwater fluxes and relate these to large scale data fields; to improve our understanding of the ITF sources waters and of the mixing processes that alter the stratification enroute through the Indonesian Seas.

APPROACH

Time series of in situ and satellite-derived data are used to study the mean and variable form of the Indonesian throughflow. Two moorings (Dec 1996-July 1998) provide the information on the throughflow within Makassar Strait. Collection of CTD stations since 1991 enable quantitative description of the throughflow pathways, water mass sources and their variability. Satellite data used is primarily altimetric data. Regional VOS XBT data collection programs provide views of the thermal structure of the thermocline, which we find are closely linked to ITF mass flux. Comparison of the Indonesian interior seas data to the varied data sets collected in the Lesser Sunda Islands and in the Australian-Indonesian Bight as well as ocean scale data sets is carried out.

WORK COMPLETED

During late 1999 and 2000 many papers were published based on the Arlindo data set. The work (summarized by Gordon, 2000) focus on a few key items: transport of the ITF (Gordon et al 1999); relationship of the thermocline to ITF (Ffield et al. 2000); intraseasonal (>90 days) variability in the ITF (Susanto et al., 2000; Sprintall et al., 2000); CFC distribution (Waworuntu et al., 2000); and heat flux into the Indian Ocean (Vranes et al., 2000). Application of the POMS model is made by Burnett et al. (2000a,b). Presently the focus is turned to spatial and temporal variability of the stratification and to more detailed treatment of the Makassar Strait mooring time series.

RESULTS

The ITF waters are drawn from the Mindanao (North Pacific thermocline) and Halmahera (South Pacific thermocline) quasi-stationary eddies between the Philippines and New Guinea. Models show that the ITF source water (North Pacific versus South Pacific) depends upon land geometry and the tropical Pacific wind fields. Observations indicate that the ITF is composed mostly of North Pacific thermocline and intermediate water flowing through Makassar Strait consistent with model results which show that the westernmost deep channel, Makassar Strait, carries the bulk of ITF. While some Makassar throughflow exits the Indonesian Seas within Lombok Channel, most turns eastward in the Flores Sea to enter the Banda Sea before entering the Indian Ocean. In the deep channels east of Sulawesi, South Pacific water infiltrates (isopycnally) into the lower thermocline of the Banda Sea and dominates the deeper layers through density-driven overflow. Estimates of ITF transport within various passages of the Indonesian Seas are shown in Fig. 1 (from Gordon, 2000).

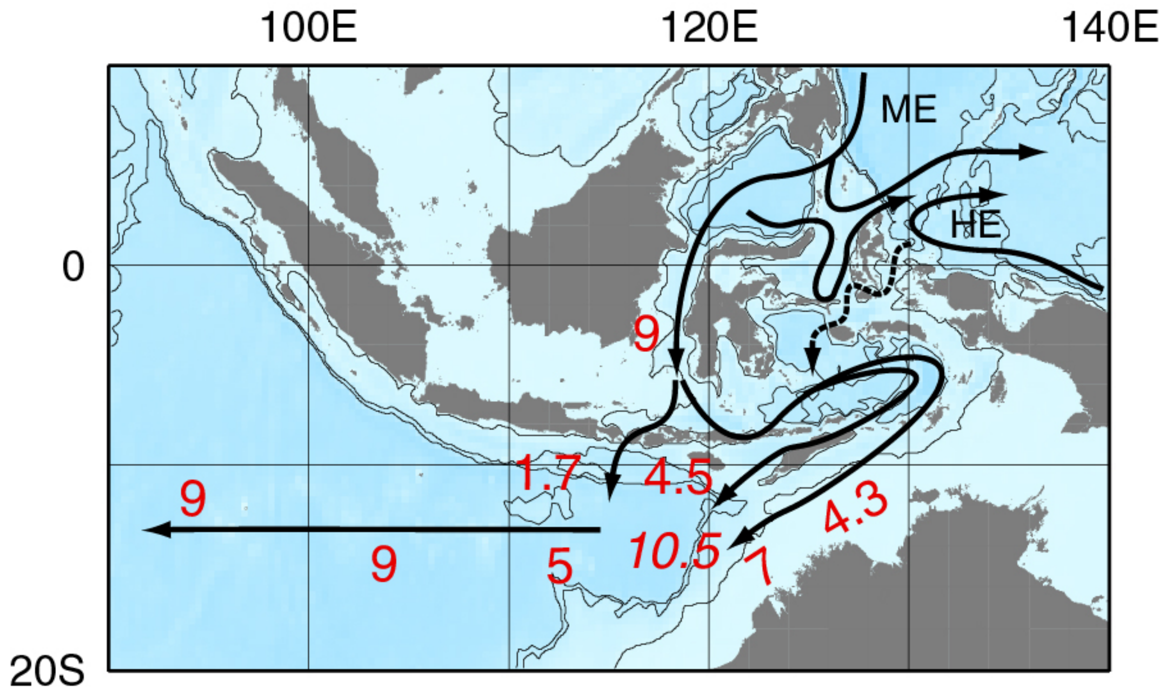

Figure 1: Pacific to Indian Ocean transports in Sv (10^6 m^3s^{-1}) through the Indonesian Seas as estimated by various investigators (Gordon, 2000). As these values represent different time periods, they do not reflect the climatic mean. The 10.5 Sv in italics is the sum of the flows through the Lesser Sunda passages, in rough agreement with the Makassar Strait throughflow. The throughflow within the eastern channels probably accounts for 1 to 2 Sv. ME is the Mindanao Eddy; HE is the Halmahera Eddy.

As part of the Arlindo program, velocity and temperature were measured at various depths at two moorings within a 45 km wide constriction of Makassar Strait near 3°S between December 1996 and June 1998. The 1997 average southward transport within Makassar Strait is 9.3 Sv, with a range of about ±2.5 Sv depending on how the surface flow is taken into account. Temperature and salinity data obtained during the Arlindo cruises (6 cruises from 1991 to 1998) indicate there is no significant return to the Pacific Ocean of Makassar Strait water along a route east of Sulawesi Island, indicating that Makassar transport feeds into the ITF. Measurements in the Lombok Strait from January 1985 to January 1986 show an average transport of 1.7 Sv. The mean transport between the sea surface and 1250 m in the Timor Passage (between Timor and Australia) measured in March 1992 to April 1993 is 4.3 Sv. The range of transport estimated within Ombai Strait (north of Timor, between Timor and Alor Island) during 1996 (December 1995 to December 1996) is 3 to 6 Sv, depending on the assumed cross-strait shear. While caution is urged as these time series measurements were made at different times and ENSO phases, Makassar Strait transport is comparable to the transport sum through the passages of the Lesser Sunda Island chain, of 10 Sv. This is also consistent with estimates of the ITF contribution to the South Equatorial Current in the Indian Ocean.

Observational and model studies suggest the ITF transport varied (by as much as ± 5 Sv) with the phase of ENSO: larger transport during La Niña condition, smaller transport during El Niño. The Arlindo mooring observations within Makassar Strait, which span the entire cycle of the strong 1997/1998 El Niño, find a correlation (r = 0.73) between Makassar transport and ENSO. During the El Niño months December 1997 to February 1998 the transport average is 5.1 Sv, while during the La Niña months of December 1996 to February 1997 the average is 12.5 Sv, a 2.5-fold difference. Most of the remaining variance of ITF transport once ENSO effect is removed is explained by the annual cycle, with a June maximum and December minimum and by intraseasonal events.

December 1996 to early July 1998 temperature and ocean current information within the Makassar Strait is used to calculate internal energy transport of the ITF and assess its influence on Indian Ocean heat divergence. Velocity and temperature values for the surface layer which were not directly measured, are extrapolated from the shallowest measurement to the sea surface. While a single temperature profile is used based on a linear interpolation from NCEP OI sea-surface temperatures to the top-most mooring temperature recorder, four different velocity profiles are employed. Energy flux is calculated as volume transport multiplied by temperature, density and specific heat, using reference temperatures between 0°C and 4°C. The mean internal energy transport averages 0.54 PW relative to 0°C, and 0.39 PW relative to 4°C for two most reasonable velocity profiles. In comparison, model heat transport values range between 0.6 PW and 1.15 PW. Energy transport varies with ENSO phase, lower during El Niño; higher in La Niña. As 1997 was an El Niño year, our energy flux value may be less than the climatic mean. The Indonesian Throughflow is advected towards Africa within the Indian South Equatorial Current, to eventually exit the Indian Ocean across 30°S within the Agulhas Current. For realistic consideration of the ITF component within the Agulhas Current, the heat flux divergence of ITF waters within the Indian Ocean north of 30°S is found to be insignificant. Therefore the ITF transports a significant amount of Pacific Ocean heat into the southwest Indian Ocean (10,000 km from the Indonesian Seas!), a result consistent with model studies.

IMPACT/APPLICATIONS

The Makassar mass, heat and freshwater fluxes obtained from the mooring data are important in evaluating the varied models of the throughflow, which until now have been poorly constrained with in situ observation. At least in preliminary view, the seasonal and interannual variability of Makassar transport seems to be very different from that seen in models, or the in the indirect or partial observation made within the Timor Sea. The Arlindo CTD and CFC data set with the mooring temperature record data will lead to a better understanding of the advective and mixing processes that shape the thermohaline stratification of the Indonesian Seas.

TRANSITIONS

The Arlindo products are of use in the development of regional and global ocean circulation models: Julie McClean (NPS) , Vladimir Kamenkovich (USM), Roxana Wajsowicz (U Maryland) and Raghuram Murtugudde (NASA/GSFC) are all engaged in considering the impact on models of the Arlindo observations. There are also non-US transitions, mainly the joint analysis of the Arlindo and JADE (French-Indonesian) program, which measured Timor Sea transports at the time of the MAK moorings, and with Gary Meyers who is monitoring the thermal field from Java to Australia.

RELATED PROJECTS

The Arlindo data collection and initial analysis was funded mainly by NSF (ends in 2000). We have a grant from NASA to study the relationship of Topex Poseidon sea level anomaly data to the Arlindo measurements within the Indonesian Seas.

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